

Section 8

Traffic Light System (TLS)

8.1. Scope and Overview

This section explains the purpose and basic elements of a “Traffic Light System” (TLS), and important considerations for developing and implementing a TLS. A TLS is a combination of seismic monitoring (Section 6) of ground motion (Section 5) and a decision process. These are used as tools to manage the potential risk of induced seismicity. The risks associated with induced seismicity can also be mitigated by injection site characterization/selection, injection well design and construction features, control over well operational factors, and even by the design of structures to withstand ground motion. As discussed in Section 4, depending on a combination of unique site-specific factors, different levels of ground motion could potentially be induced or triggered by wastewater injection. The following sections provide important considerations in the development and implementation of a TLS, along with recent examples of actual systems.

8.2. What is a Traffic Light System?

The name “Traffic Light System” is based on a simplified comparison to the lights that manage automobile traffic risks by changing colors to indicate when it is safe to go (green), when caution should be exercised (yellow), and when to stop and wait until conditions are safe (red). Thus, a TLS applies a decision process to seismic data to determine what actions and information are needed (if any) to manage the potential for induced seismicity at a site. Further, an effective TLS should include a process for interaction with the injection well operator in developing site-specific actions to mitigate the potential for induced seismicity, including: gathering more data, changing operational parameters (such as rates and pressures), pausing or stopping injection (if ultimately deemed necessary), and controlled re-startup (when appropriate).

8.3. When should a traffic light system be applied?

A TLS should be applied to those operating injection well sites where seismic monitoring has been determined to be necessary due to unique characteristics of the location as explained in detail in Section 6. In addition, a TLS may use data from State-wide or regional networks, but this data may have limitations in applicability to a specific site.

The results from a TLS may also be useful for decisions on siting new wells in an area where the TLS has been implemented by providing new information about seismicity and geologic structure that may be helpful in designing and operating the new wells.

8.4. Basic Elements of a Traffic Light System

Since the risk from induced seismicity depends on characteristics of the location and operation where injection is occurring, the TLS needs to be flexible and adaptive. The details of each TLS element should be determined

based on site-specific and operations-specific characteristics, for example as a condition of a well-specific permit application.

8.4.1. Stated Goal

The general goal of a TLS is to use seismic monitoring data collected during injection well operations to manage the potential for induced ground motion, if any. Each State must define what their management goal includes for their TLS. A clear statement of this goal will be the basis for the other elements of the TLS. Examples of TLS goals could include:

- The ability to identify unusual seismic activity (if and when it occurs) that may be attributable to waste water injection at a site
- The ability to indicate when induced seismicity at a site (if and when it occurs) has the potential to:
 - Damage structures
 - Be felt by the public, and/or
 - Cause serious disturbance to the public (“serious disturbance” must be defined)
- The ability to support determination of appropriate site-specific actions (if needed) to mitigate potential induced seismicity

8.4.2. Seismic monitors

The decision process inherent to the TLS is based on interpretation of data on ground motion obtained from seismic monitors. Monitoring is discussed in detail in Section 6.

8.4.3. Thresholds

A TLS has “thresholds” used to guide entry into different parts of the decision process for actions that should be taken to manage induced seismicity. These thresholds are defined based on seismic monitoring data and the risk management goals of the TLS, and are typically named as colors consistent with the traffic light analogy (i.e. green, yellow and red). Note that a TLS does not have to be limited to three thresholds. The number of thresholds (lights) should be developed based on the ability to use available data to identify different levels of ground motion that warrant different types of action to ensure risk management goals are maintained. Examples of thresholds used in traffic light systems for induced seismicity are provided below in Section 8.7.

8.4.4. Decision process

A key element of a TLS is the decision process. The decision process is used to interpret seismic data and determine the best actions for managing the potential for induced ground motion and maintaining TLS management goals. This decision process should include steps for interaction with the injection well operator in developing site-specific actions to manage the potential for induced seismicity, including but not limited to:

- Gathering more data and/or more detailed analysis of data
- Changing operational parameters (such as rates and pressures) to reduce ground motion and risk
- Pausing injection
- Controlled re-startup (if possible)
- Supplemental monitoring
- Permit modification
- Stopping injection and closing well, if needed

It may be helpful to represent the general decision process, or parts of the process, in the form of a flow diagram or decision tree. Examples can be found in some of the case studies described in Section 8.7.

The TLS should not only be a process to pause or halt operations, but also include a process to restart and continue operations, if and when TLS management goals can be achieved.

8.5 Considerations When Developing a Traffic Light System

The purpose of a Traffic Light System is to employ a protocol to manage the risk associated with a potential hazard. In general terms, a traffic light system is an “*If...then*” risk management system; “if this occurs...then this happens”.

8.5.1 “If This...”

To develop the “if this occurs” portion of a Traffic Light System, the “this” must be defined. In the case of seismicity, the “this” would be a seismic event or earthquake; however, some states have applied a Traffic Light System to the permitting of injection wells.

When applying the traffic Light System to earthquakes, the definition of “this” must include the size of the event and any potential impact the event may have on structures and the public.

The size of the event can be based upon the magnitude of the event at the hypocenter (subsurface location of the event) or the ground motion at the epicenter (at the surface where a seismometer is located). The use of magnitude is the standard used to define earthquakes, but it requires mathematical modeling that is dependent upon local geology and depth from the surface to the hypocenter. The modeling required can be developed from historic seismic events for a given area. Models from one area can be used in another area if adjusted for the variances in geology and depth. However, the accuracy of the model decreases with distance from the calibration model area.

The use of surface ground motion, Section 4, is a way to directly relate the size of an event with its potential impact. The mining industry has been using ground motion to define seismic activity of concern for years, the USGS uses ground motion to develop hazard maps used by the insurance industry to define high risk areas, building architects/engineers use ground motion to develop construction codes, and ground motion is monitored during seismic vibroseis data acquisition to keep source generated surface waves below levels that may cause damage to nearby structures.

Given a set of ground motion detections, at the epicenter, and the depth and distance to the hypocenter, it is possible to define the rate of ground motion decay an event would have “x distance” from the hypocenter. This information can then be used to define the area of impact for a given event with consideration to areal extent and local subsurface characteristics.

The next thing to consider is the definition of the event size (magnitude or ground motion) that could trigger a specific “then”. As mentioned previously in this section, one has to understand the desired goal of one’s traffic light system as it relates to impact. As part of this assessment the size of the potential impact including areal extent, demographics and local surface characteristics must be defined. In most cases, the impact of smaller induced seismic events (< M 3.0) is localized (< 1 county) whereas the areal extent of larger events (M4.0 – M5.0) can be regional (1-3 counties). Local surface characteristics to consider include land use structural design requirements (codes), structural integrity of existing structures (dwellings, buildings, and roads), presence of critical structures or businesses, presence of reservoirs with dams, and other similar elements. Particular care should be taken in areas of high population density as such areas are especially vulnerable to impacts from ground motion due to the density of structures.

Other considerations in the development of a Traffic Light System includes the presence of faults, (depth, size, orientation with respect to regional stress conditions), basement depth, characteristics of the stratigraphic column and the historic seismic history of the area.

8.5.2 “...Then This”

The generic Traffic Light system has 3 defined levels of “if this” that result in 3 different “then this”. As the name suggests, the general definitions of the levels are based upon a standard traffic light recognizing that additional levels may be added as necessary.

- Green Light – proceed to operate within conditions of permit
- Yellow (Amber) Light – proceed with caution
- Red – stop until light changes back to yellow or green

Under a green light, operations may proceed subject to the conditions of the disposal permit. Under a yellow light, operations may be modified to reduce seismicity or curtailed pending an investigation. Under a red light, operations may be suspended until circumstances change. The definition of the “then this” for a red light is thus directly related to what light you want to change to: yellow or green. However, in either case the framework of the response is the same; investigation followed by modified operations as necessary to achieve the desired yellow or green light status.

The nature of any investigation is highly dependent upon the events that preceded the change in light color (level) and the complexity of the issue. The investigation therefore must be site specific and scalable. A group of subject matter experts has previously identified several tool boxes that can be used to define the elements to be considered when developing an investigative plan. The tool boxes are presented below.

Tool Box for the Evaluation of Potential Hazard (seismic activity)

Item	Data, Resources and Tools
Key geologic horizons and features	Data from existing wells, reflection/refraction seismic data, and gravity/magnetic data. Fault presence assessment from mapped horizons and coherency 'and tracking'.
Regional stress assessment	World stress map, Stress literature, physical measurement, stress estimates from seismic and/or nearby well logs. Model effect on the reservoir and surrounding rocks from stress changes associated with fluid injection.
Surface features	USGS geological maps, published reports.
Ground conditions	Consolidation, saturation, composition, proximity to basement from State and USGS maps.
Ground response	Expected peak velocities, acceleration, and spectral frequency. Refer to local civil engineering codes. Models from USGS, state agencies and academia.
Local seismic events	Academic (e.g. IRIS), State, and industry surveys. If not available then regional or local dedicated network of seismometers and ground motion sensors. Establish magnitude, frequency of occurrence, and ground motion relationships.
Reservoir characterization	Rock type, facies, age, matrix composition, porosity types, depth, thickness, and petrophysical properties. Lateral extent and continuity, proximity to outcrop, proximity to basement, lateral barriers and conduits, compartments, bounding layers and intervening formations to basement, sealing rocks in system.
Reservoir properties	Permeability, porosity, natural fracture porosity, storativity. Mechanical properties: fracture gradient, closure pressure (ISIP), Young's Modulus, Poisson's Ratio, cohesion, coefficient of friction, pore pressure, lithostatic pressure, hydrostatic pressure, horizontal stress magnitudes and azimuth.
Disposal conditions	Initial saturation, salinity, pore pressure, static fluid level. Fluid injection rates, pressures, cumulative volumes

Tool Box for the Evaluation of Potential Risk (Impact)

Item	Data, Resources and Tools
Population	Survey 10 mile radius, nearby population centers. Assess the regional population density. Comfort or familiarity with seismic events – assess potential nuisance thresholds
Structures and Infrastructure	Summary of buildings, roads, pipelines, electric grid Critical infrastructure – e.g. Hospitals, schools, historical sites Construction practices, materials Local codes, seismic event ready? Density of structures in the area
Dams, Lakes, Reservoirs	Presence of dams, reservoirs. Ages, type of impoundment (i.e. earthen vs concrete construction) History of fill/drawdown Substrate – material and known faults
Environmental	General description of local ecology Special environmental hazards
Intangible	Goodwill, trust, reputation
Risk	Probabilistic models with both chance of occurrence and estimated ranges of potential outcomes for damage assessments, e.g. from HAZUS (USGS)

Tool Box for Monitoring

Item		Data, Resources and Tools
Operations	Fluid parameters	<p>Continuous monitoring and recording of injection rates, and pressures.</p> <p>Daily and cumulative injection volumes measured and recorded.</p> <p>Injectant properties noted: e.g. salinity, chemistry.</p>
	Reservoir	<p>Fluid levels, shut-in pressure, pore pressure, changes in conditions.</p> <p>Pressure transient behavior – e.g. falloff, step rate tests</p> <p>Well performance and reservoir flow behavior (Hall plots, Silin plot) Storage/transmissivity</p>
Seismicity	Regional	<p>Establish baseline conditions from USGS and other regional sources.</p> <p>Maintain catalog of events from USGS and other regional sources.</p> <p>Identify excursions from historical trends (temporal and spatial).</p> <p>Note surface effects from seismic events recorded.</p>
	Local	<p>Install local array sufficient to locate events in the subsurface near the injection zone.</p> <p>Deploy sensors capable of measuring peak ground acceleration and velocity in the vicinity of the injection site.</p> <p>Monitor possible “traffic light” events within a specified distance of the well.</p> <p>Evaluate whether any observed seismic events are induced or naturally occurring.</p> <p>Report potentially induced threshold events established in the Risk Management plan that initiate mitigation steps.</p>

8.6 Development of a Traffic Light System.....Team...It has been recommended that we may not need this section given what is already included...especially the great job Jessie did in researching and developing Section 8.7...thoughts????

4 commenters agreed...no one disagreed

8.7 Examples of Current Approaches

8.7.1 Ohio – Salt Water Disposal

8.7.1.1 Background

According to the USGS, Ohio has a history of moderate intensity earthquakes. An intensity VII earthquake caused damage in western Ohio in June of 1857, an earthquake near Columbus in 1884 was felt as far away as Washington, D.C. Other series of earthquakes have occurred in 1926, 1930, 1937, 1943, and 1952.ⁱ Two larger earthquakes, magnitude 4.5 and 5.0, were measured by USGS in 1986 in the northeast and far west portions of the state. Other smaller earthquakes, magnitude 3.0 to 4.0, have been measured in 1974, 1975, 1977, 1988, 1991, 1995, 2007, and 2009.ⁱⁱ

Starting in March 2011, a series of ten earthquakes ranging in magnitude from 2.1-2.7 occurred near Youngstown, in the Northeast corner of the state. Though no significant damage was reported from the earthquakes, the Ohio Department of Natural Resources (ODNR) began investigating their potential ties to underground injection wells in the area. On December 30th, 2011, after determining the most recent quake on December 24th, 2011 was centered just 2000 feet below an injection well, the ODNR asked that injection be halted at the well. Injection was halted that day, but two days later, a magnitude 4.0 earthquake struck the same general area near the well. Immediately, the ODNR instituted a moratorium on injection in a 5 mile radius of the earthquake, and in 2012 began drafting new regulations regarding the potential for induced seismicity. On October 1, 2012, the new regulations were put into effect.

8.7.1.2 Current Approach

Under the regulations, operators are required to take a number of steps as part of its Traffic Light Systemⁱⁱⁱ

1. Geologic data review for known faulted areas within the state
2. A complete suite of geologic logs (at least gamma ray, density-neutron, and resistivity logs)
3. Plug back with cement any well drilled in the Precambrian basement rock
4. A submission of a plan for monitoring any seismic activity that may occur
5. Measurement or calculation of original downhole reservoir pressure prior to injection
6. Step-rate injection tests to establish formation parting pressure and injection rates
7. Continuous pressure monitoring systems are required, with electronic records for ODNR

8. Automatic shut-off if the fluid injection pressure exceeds a maximum set by ODNR
9. Electronic data recording system for tracking fluids injected

Upon review of the data, the Chief of the Ohio Division of Oil and Gas has the authority to withhold injection authority, require plugging of the well, or allow injection to commence. Further, the chief may also implement a graduated maximum allowable injection pressure.^{iv} In addition to the new regulations, ODNR has developed a significant seismic monitoring array. A combination of ODNR installed monitors and privately installed monitors all feed data into a single network, OhioSeis. The division also employs a set of portable seismic monitoring stations. The ODNR places them around new Class II injection wells and monitors prior to commencement of injection. If there is no evidence of seismic events felt at the surface after 6 months of monitoring, the portable station will be moved to a new Class II location.^v

8.7.2 Colorado – Salt Water Disposal

8.7.2.1 Background

The USGS considers Colorado to be a state of minor earthquake activity, but it is not without historical events. The first known reference to an earthquake in Colorado occurred on December 7, 1870, with the first one causing damage to Denver was an estimated 6.6 magnitude earthquake on November 7, 1882.^{vi} An intensity VI earthquake occurred November 15, 1901, and again on September 8, 1944. Other significant earthquakes have struck in 1955, 1930, 1971, 1975, and at least once per year between 1978 and 2015.^{vii}

Perhaps the most famous series of earthquakes historically in Colorado are the Denver series around the Rocky Mountain Arsenal, in the 1960s.^{viii} In 1961 a 12,000 foot well was drilled at the Arsenal, for disposing waste fluid from Arsenal operations. Injection started in 1962, and a series of earthquakes occurred with increasing intensity until after the injection ceased in 1965. Earthquakes in the area continued into the early 1970s causing damage to the Commerce City, Denver, and Boulder areas. More recently, an earthquake series in the Raton Basin area of northern New Mexico and southern Colorado has been potentially linked to injection activities in the area, leading up to a 5.3 magnitude event in August 2011.^{ix} Earlier that year, the COGCC expanded its UIC permit review process to include a seismicity review.^x

8.7.2.2 Current Approach

The safeguards currently in place in Colorado allow the COGCC to consider and require the following in permitting^{xi}:

1. Limits on injection volumes
2. Injection pressures (must be below fracture gradient)
3. Historical and geologic data review by the Colorado Geological Survey

According to the COGCC, “The CGS uses geologic maps, the USGS Earthquake database, and area-specific knowledge to provide an opinion of seismic potential. If historical seismicity has

been identified in the vicinity of a proposed Class II UIC well, COGCC requires an operator to define the seismicity potential and the proximity to faults through geologic and geophysical data prior to any permit approval.”^{xii} Using the data from this review, the COGCC permit writer calculates a maximum injection volume, which is restricted to a ¼-mile radial volume and the height of the formation.^{xiii}

In June 2014, Colorado’s Traffic Light System was put to the test. The COGCC determined that two seismic events may have been linked to an injection well near Greeley, CO. At the time, they ordered the well to stop injecting for 20 days, while gathering more information.^{xiv} Eventually, the operator was allowed to continue operating the well at a lower pressure and volume, but only after plugging back the well 400 feet and installing a seismic monitor, providing a 2.5-mile radius of review. If additional seismic activity were to take place in that area, the well could be shut down a second time.^{xv}

8.7.3 Oklahoma – *Salt Water Disposal*

8.7.3.1 Background

Oklahoma has an extensive history of seismic events, dating back to the beginning of the 19th century with the New Madrid series, (centered in Arkansas and Missouri) and has documented earthquakes ranging in the magnitude 5.5 range, and intensity VII range. Earthquakes occurred primarily between 1918 and 1929, including a 5.5 magnitude earthquake in 1952 with an intensity of VII. Later earthquakes occurred in 1953 and 1956 were followed by more medium intensity quakes in the 1960s.^{xvi} Later earthquakes above magnitude 4.0 were recorded in 1995, 1997, but the frequency of such quakes started to increase significantly in 2010, with 34 earthquakes of magnitude 4.0 or greater occurring since February of 2010.

Noting a trend toward increased earthquake frequency, and led by research from the Oklahoma Geological Survey^{xvii}, the Oklahoma Corporation Commission began working on mitigation techniques before the Prague earthquake of 2011, later adopting new practices and approaches.

8.7.3.2 Current Approach

The Oklahoma model began with areas of interest centered on previously occurring strong felt earthquakes. Within that area of interest, the OCC, OGS, and operators work in a cooperative manner to take precautionary measures where there may be potential concern. In 2013, the OCC instituted a Traffic Light approach, updated again in 2014 and March of 2015, which requires a seismicity review for any proposed disposal well within an area of interest (within ten kilometers of a swarm or previous 4.0 event), or within 3 miles of a stressed fault in the absence of seismicity. These rules require reporting and recording of well pressure and volume for Arbuckle disposal wells in the state, and additional mechanical integrity tests for higher volume wells.^{xviii} Another update in March of 2015 was the requirement that all wells within the new area of interest be proven to be completed or plugged back above the crystalline basement rock or granite wash sands. Operators have until April 18, 2015 to prove this has been done or risk reducing injected volumes by half.^{xix}

8.7.4 California - Geothermal

8.7.4.1 Background

California has a well-documented history of large, damaging earthquakes, and concerns over induced seismicity have been at the forefront of the discussion around many different human activities. California is the second most seismically active state in the US, only behind Alaska, with 4895 events of magnitude greater than 3.5 between 1974 and 2012.^{xx} California has been the epicenter for more than a dozen 7.0 and greater earthquakes since the 1800s, and while none are thought to be induced by human activity, there is still concern around potential impacts of geothermal activities on already stressed faults.

The Geysers and Coso geothermal fields have a considerable history of injection induced seismicity, including events up to magnitude 4.0, in addition to thousands of microquakes induced annually during some periods. The geothermal energy production process is a mature industry and the mechanisms of induced seismicity are better understood than in other areas of the country as a result.^{xxi} Due to the experience California has had with their Traffic Light System over a prolonged period of time, and the similarity of mechanisms between geothermal injection and salt water disposal injection, the Traffic Light System for geothermal activities has served as an example and information source for other state approaches.

8.7.4.2 Current Approach

The Environmental Protection Agency (EPA) has delegated authority to regulate Class V injection wells to the BLM on federal lands. Under this agreement, the BLM can assign conditions of approval in cases where induced seismicity is observed. The BLM uses its own Traffic Light approach which allows enhanced geothermal systems to proceed so long as ground motion doesn't exceed Mercalli IV. However, if the activity is to approach the Mercalli V ground shaking level, then the operation is required to be scaled back. Finally, if the operation results in Mercalli VI or greater events, the operation is to cease entirely.^{xxii}

The DOE has also developed a guidance protocol for geothermal induced seismicity, published in 2012.^{xxiii} While not a regulatory authority, it provides guidance around mitigating seismicity risk around geothermal operations. As a general outline, the DOE suggests the following stepwise process:

1. Perform a preliminary screening evaluation
2. Implement an outreach and communication program
3. Review and select criteria for ground vibration and noise
4. Establish seismic monitoring
5. Quantify the hazard from natural and induced seismic events
6. Characterize the risk of induced seismic events
7. Develop risk-based mitigation plan

The key difference between the DOE recommended approach and many of the others is that it takes into consideration social consequences and acceptance of the technology and of seismic

events. In areas that are less populated, or with a population more accustomed to seismic activity for example, a higher threshold would be applied under the DOE recommendations. Conversely, placing operations near key infrastructure or a population center would be more difficult.

8.7.5 Illinois – Salt Water Disposal & Wells Accepting Hydraulic Fracturing Fluids

8.7.5.1 Background

Illinois has a history of seismic events, dating back to the end of the 18th century with a felt event in 1795 and had reported earthquakes averaging about 1 per year before seismograph stations. With more and more seismograph stations on the national seismic network, the average over the past decades has been about 4 felt and higher events per year. Events in the low magnitude 5s have occurred in 1838, 1891, 1909, 1968 and 2008. About 31 magnitude 4s have been reported starting in 1857 and one swarm of 150 earthquakes occurred with magnitudes ranging from 0.2 to 3.6 in 1983-1984.

8.7.5.2 Current Approach

No reported seismic events have been reported with disposal wells in Illinois, but a Traffic Light System was initiated in Illinois along with regulations governing high volume hydraulic fracturing (HVHF) in horizontal boreholes. The traffic light governs the operation of Class II UIC wells that inject any Class II fluids or hydraulic fracturing flowback from HVHF operations as defined by the Hydraulic Fracturing Regulatory Act^{xxiv}. This does not include Class II wells used for enhanced oil recovery operations.

The 3 color light system is based on magnitudes and/or number of magnitude events per year within defined distances of the injection wells. Three Yellow alerts of magnitudes 2.0 to < 4.0 within 6 miles of a well leads to reduced volume and development of planned actions going forward and a Red alert is defined as a magnitude at or above 4.0 within 6 miles of the well leads to immediate cessation. The regulatory department has discretion to issue cessation orders to wells which accept the hydraulic fracturing fluids from HVHF operations for seismic events within 10 miles of the well when necessary if there is imminent danger to the health and safety of the public or significant damage to property. This is a general overview and more specific actions can be found in the Illinois Oil and Gas Act, Section 240.796^{xxv}.

8.7.6 Illinois – CO₂ Geologic Storage *do we want to include as it is not injection???*

8.7.6.1 Background

Archer Daniels Midland in Decatur, Illinois has two Class VI UIC injection wells for the purpose of geologic sequestration of carbon dioxide from its agricultural products and biofuel production facility. One well has completed injection of 1 million metric tons during a 3 year time period and is now shut in. Subsurface seismic monitoring arrays started recording any microseismic activity from 1.5 years before injection, through injection and now in the post injection time period. Well 2 is expected to become operational near the end of 2015.

8.7.6.2 Current Approach

Both permits contain the same traffic light methodology of seven threshold conditions associated with 5 color operating states. This can be found under the emergency and remedial response plan of both permits^{***xxvi}. Threshold conditions are based on magnitudes, number of specific magnitudes per time period, felt events and damage. Felt and damage are defined on specific criteria. Each threshold has numerous response action steps with each for notification of UIC Program Director, project participants, and operational review leading to corrective actions.

8.7.7 Canada – Hydraulic Fracturing, Water Flooding and Salt Water Disposal

8.7.7.1 Background

British Columbia has a history inter-plate seismic activity along its Pacific coast. It is estimated that a 9.0 magnitude event took place on January 26, 1700, judging by the tsunami chronicled in Japan. Since that time there have been magnitude 7 and 8 events in the 1940s, 1970s, and a 7.7-magnitude event in 2012. Historical seismicity is much lower in magnitude and frequency further inland where unconventional oil and gas field development has been particularly active since 2005. This relatively quiet background seismicity has been punctuated by periods of localized seismicity associated with the Eagle/Eagle West water floods (1984-1994), Horn River Basin hydraulic fracturing^{xxvii} (2009-2011) and Montney trend hydraulic fracturing^{xxviii} (2005-present) and waste water disposal wells. The provincial government, through its Oil and Gas Commission (BCOGC) has intervened in several instances and ordered the deployment of local seismicity monitoring and alterations to completion and injection programs. The BCOGC has also issued recommendations on how the industry should assess the risks associated with induced seismicity, and potential mitigation techniques, explained below.

Alberta has a history of relatively infrequent and low magnitude natural seismicity. This seismicity is primarily associated with the front ranges of the Rocky Mountains along its western border with British Columbia. Alberta too, however, has recorded seismicity that has been associated with oil and gas industry activity. Among these are the Snipe Lake local magnitude (M_L) = 5.1 event (1970)^{xxix}, the Rocky Mountain House events (M_L < 3.4, 1980)^{xxx} and the Fox Creek/Crooked Lake event cluster that is most well known for its M_L = 4.4 event^{xxxi} in January, 2015. In response to the latter Fox Creek event, the Alberta Energy Regulator (AER) is the only Canadian regulator to have issued a general order (Subsurface Order No. 2)^{xxxii}. This order is limited to the 'Duvernay Zone' in an area near Fox Creek/Crooked Lake.

8.7.7.2 Current Approach

Both British Columbia and Alberta have regulations and well licensing requirements that govern waste water disposal and water flood injection. These regulations primarily address concerns around maximum injection pressures and injectivity rates to ensure safe well design and fluid containment.

The BCOGC typically has intervened in cases that demonstrate sustained M_L > 2.0 seismicity. In cases where there are potential induced events ranging between M_L 2.0 and 4.0, local seismicity

Commented [JHB1]: Break into BC and Alberta??

monitoring and more complete pressure and volume data are usually ordered. In these relatively low seismic magnitude cases, reports of disturbance from the public also plays an important role in determining the regulators response. In cases where potentially induced events are recorded at a M_L of 4.0 or greater, the BCOGC recommends that operations cease until mitigation measures are approved. In those cases, well operations may resume if the BCOGC is satisfied with the mitigations put in place. More formalized permit conditions that cover both water disposal and hydraulic fracturing operations are expected from the BCOGC in 2015.

The rules for the defined Duvernay Zone near Fox Creek, Alberta are more formalized. It states that well licensees who will hydraulic fracture wells are required to:

1. Assess for the potential for seismicity.
2. Establish and be prepared to implement a plan to monitor, mitigate and respond to induced seismicity.
3. Be capable of detecting and immediately report local magnitude greater than 2.0+ within 5km of their operations. Operations may proceed as normal if no events above a local magnitude of 2.0 are detected (Green Light).
4. Implement a response plan for local magnitude 2.0+ events. (Yellow Light)
5. Immediately cease operations for local magnitude 4.0+ events located within 5km of their operations. (Red Light)

Operations may resume if: the operator presents a plan for modified operations which is approved by the AER and implemented by the operator.

8.7.8 United Kingdom – Hydraulic Fracturing

8.7.8.1 Background

Hydraulic fracturing has been shown, in rare cases, to induce small magnitude seismic events. The main reason for this is the mechanisms involved. According to the US Department of Energy:

“Hydrofracturing is done by injecting fluid into the subsurface to create distinct fractures in order to link existing fractures together. This activity creates additional permeability in the subsurface, which facilitates extraction of in situ fluids (such as oil and gas). Hydrofracturing is distinct from many types of shear-induced seismicity, because hydrofracturing by definition occurs only when the forces applied create a type of fracture called a tensile fracture, or “driven” fracture. Shear failure has been associated with hydrofracturing operations, as the fluid leaks off into existing fractures, but due to the very-high-frequency nature of tensile failure (seismic source at the crack tip exclusively), only the associated shear failure is observed by microseismic monitoring. However, hydrofracturing is such a small perturbation, it is rarely, if ever, a hazard when used to enhance permeability in oil and gas or other types of fluid-extraction activities. To our knowledge, hydrofracturing to intentionally create permeability rarely creates

unwanted induced seismicity that is large enough to be detected on the surface—even with very sensitive sensors—let alone be a hazard or an annoyance.

However, some cases have been observed that were felt at the surface. In the UK during April and May of 2011, a hydraulic fracturing treatment near Preese Hall resulted in a local magnitude of 2.3 and a later event at local magnitude of 1.5. There was no damage or injury reported from either of the cases, but in the interest of caution, the UK Department of Energy & Climate Change instituted a moratorium on hydraulic fracturing until detailed studies and recommendations could be developed. The moratorium was eventually lifted, and the UK has adopted a Traffic Light System with triggers at much lower magnitudes than those of the previously mentioned areas.^{xxxiii}

8.7.8.2 Current Approach

According to an infographic published by the UK Department of Energy & Climate Change^{xxxiv}, the UK follows a fairly straightforward Traffic Light System. Injection activities around hydraulic fracturing which record no seismicity greater than 0.0 on the Richter scale may proceed as planned. Those activities generating events at magnitudes between 0.0 and 0.5 must proceed with caution, at reduced rates and with greater monitoring requirements. Finally if an event is recorded that is potentially induced at a magnitude of greater than 0.5, injection is suspended immediately. Also included in the requirements are a pre-project Hydraulic Fracturing Programme, which must review the available information on faults in the area, and confirm the well is not drilled into or close to existing faults.^{xxxv}

8.7.9 El Salvador – Geothermal

El Salvador lies in a region of the world with frequent volcanic activity, and there is great opportunity to develop geothermal. Currently, 24% of the electricity generated in El Salvador is geothermal, mainly by two energy production areas, the Ahuachapán region and the Berlín region.^{xxxvi} In 2003, a hydraulic stimulation was carried out in the Berlín field, in an area with previous significant and damaging natural seismic activity. As a prerequisite to development, a Traffic Light System was developed in an attempt to limit any induced seismic activity in the area.

The conceptual framework of the Traffic Light System was similar to many of the other programs listed in this section, and it predates most of them. According to a study published by Elsevier^{xxxvii}:

A system is ultimately needed that can, in effect, be operated as a traffic light, allowing those on site to determine, simply and rapidly, whether it is possible to proceed (green), to invoke caution (amber), which may mean adjusting levels of operation (in this case, the hydraulic injection rate), or simply to stop (red).

Main among the concerns at the time was not the potential for heavily damaging induced seismicity, but instead avoiding the potential that smaller events, caused by the energy production project, could potentially render structures more susceptible to much larger, natural events. The Traffic Light System applied in El Salvador was considered to be a useful and effective tool, however, there was not nearly the amount of induced seismic activity as what was expected at the time. Because of this, the system mainly placed the energy project in a green light scenario.

8.7.10 Switzerland – Geothermal

Basel, Switzerland sits atop a historically active fault line – most of the city was destroyed in 1356 by what is estimated to be a magnitude 6.5 earthquake. The Basel enhanced geothermal systems project, starting in December 2006, and ultimately cancelled in 2009, operated under a 4 stage Traffic Light System intended to reduce seismic risk from the geothermal activities. Between December 2006 and March 2007, seismic equipment detected more than 13,500 potential events connected to the project, most of which were small and not felt at the surface, but with nine events at a magnitude of 2.5 or greater. This four stage Traffic Light System was based on similar criteria as the El Salvador approach, including public response, local magnitude, and peak ground velocity. What made the Basel project unique was all four stages of the traffic light were activated, and the well was shut in. The four stages of the Traffic Light System for the Basel project were:

1. Green – continue as planned
2. Yellow – continued, but not increased in rate or pressure
3. Orange – activity stopped
4. Red – Activity stopped and well bled off

The Basel Traffic Light System was not considered adequate for monitoring the project. For one, the project proceeded to the red stage and had to be bled down. Second, the seismic risk in the area has been increased over the past several years as a result of the project, even though it was shut down within a few days.^{xxxviii} One approach to help remedy future similar situations is an “Adaptive Traffic Light System” which make probabilistic forecasts about expected future seismicity based on a range of parameters. These methodologies would predict the resulting seismic activity after shut-in has occurred.

8.7.11 The Netherlands – Gas Production

8.7.11.1 Background

The Groningen gas field, located in the northeast portion of the Netherlands, is the largest gas field in western Europe. Discovered in 1959 (at the time the largest in the world), the field has produced approximately 70 tcf of gas since production started in 1963. KNMI, the Netherlands Meteorological Institute, has identified 720 induced earthquakes associated with the gas field from 1986 until the start of 2013^{xxxix} - most notably, the August 16, 2012 $M_w=3.6$ earthquake

near Huizinge (Groningen province) that resulted in more than 3000 damage claims and a reassessment of the seismic hazard maps of the region. Most of these quakes are a result of a change in the loading conditions on extensional faults that cross-cut the reservoir (~3km depth) due gas production.^{xi} Of those 720 events, 234 had a magnitude of 1.5 or higher. In 2013, the State Supervision of Mines reported that the frequency of earthquakes had increased, raising questions about the previously assumed maximum magnitude of the induced quakes being set at 3.9 – which is very close to to the recorded 2012 $M_w=3.6$ earthquake. To determine the best path forward, the Dutch government commissioned 14 studies, which have since been published in 2014.^{xli} As a result of the studies’ findings – that increased production can lead to more frequent and stronger earthquakes – the Dutch government set a cap on production at 16.5 billion cubic meters for the first 6 months of 2015, and is considering cutting output to a cap below 39.4 billion cubic meters for 2015.^{xlii}

8.7.11.2 Current Approach

The Netherlands does not have a formal Traffic Light System in place for responding to induced seismic events. Decisions are being made by a process of informed discussion with the politicians and the regulator. Current mitigation efforts have been focused on production reductions and improved seismic monitoring.

ⁱ <http://earthquake.usgs.gov/earthquakes/states/ohio/history.php>

ⁱⁱ Earthquakes found using <http://earthquake.usgs.gov/earthquakes/search/>

ⁱⁱⁱ http://www.gwpc.org/sites/default/files/events/white%20paper%20-%20final_0.pdf

^{iv} http://www.gwpc.org/sites/default/files/event-sessions/Tomastik_Tom_1.pdf

^v http://www.gwpc.org/sites/default/files/event-sessions/Tomastik_Tom_1.pdf

^{vi} <http://www.colorado.edu/geolsci/faculty/pdf/sheehanhughes.pdf>

^{vii} <http://earthquake.usgs.gov/earthquakes/states/colorado/history.php> and found using <http://earthquake.usgs.gov/earthquakes/search/>

^{viii} <http://www.colorado.edu/geolsci/faculty/pdf/sheehanhughes.pdf>

^{ix} J. L. Rubinstein, W. L. Ellsworth, and A. McGarr, “The 2001-Present Triggered Seismicity Sequence in the Raton Basin of Southern Colorado/Northern New Mexico,” talk delivered at the Seismological Society of America Annual Meeting, Salt Lake City, UT, April 19, 2013, pp. Abstract #13-206.

^x <http://cogcc.state.co.us/library/InducedSeismicityreview.pdf>

^{xi} http://www.gwpc.org/sites/default/files/events/white%20paper%20-%20final_0.pdf

^{xii} <http://cogcc.state.co.us/library/InducedSeismicityreview.pdf>

^{xiii} http://www.gwpc.org/sites/default/files/events/white%20paper%20-%20final_0.pdf

^{xiv} <http://www.coloradoan.com/story/news/local/2014/06/24/second-earthquake-one-month-shakes-greeley-area/11314359/>

^{xv} <http://kbhenergycenter.utexas.edu/2014/09/12/seismic-activity-and-hydraulic-fracturing/>

^{xvi} <http://earthquake.usgs.gov/earthquakes/states/oklahoma/history.php>

^{xvii} http://www.ogs.ou.edu/pubsscanned/openfile/OF1_2011.pdf

^{xviii} <http://stateimpact.npr.org/oklahoma/2014/03/13/regulator-votes-to-adopt-new-rules-for-disposal-wells-in-earthquake-prone-region/>

^{xix} <http://www.oeta.tv/blogs/onr/new-rules-for-disposal-wells-to-avoid-earthquakes/>

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- ^{xx} http://earthquake.usgs.gov/earthquakes/states/top_states.php
- ^{xxi} http://esd.lbl.gov/research/projects/induced_seismicity/egs/history.html
- ^{xxii} Induced Seismicity Potential in Energy Technologies, August 14, 2013 – National Academies Press
- ^{xxiii} Available at http://esd.lbl.gov/FILES/research/projects/induced_seismicity/egs/EGS-IS-Protocol-Final-Draft-20120124.PDF
- ^{xxiv} <http://www.dnr.illinois.gov/adrules/documents/62-245.pdf>
- ^{xxv} <http://www.ilga.gov/commission/jcar/admincode/062/062002400G07960R.html>
- ^{xxvi} <http://www.epa.gov/region05/water/uic/adm/pdf/adm-ccs1-attachment-f-err-plan-final.pdf> & <http://www.epa.gov/region05/water/uic/adm/pdf/adm-attachment-f-final-2014.pdf>
- ^{xxvii} <http://www.bcogc.ca/node/8046/download>
- ^{xxviii} <http://www.bcogc.ca/node/12291/download>
- ^{xxix} “The Snipe Lake, Alberta earthquake of March 8, 1970”. W.G. Milne. Canadian Journal of Earth Sciences. Vol. 7 (1970), P. 1564-1567.
- ^{xxx} “Earthquakes near Rocky Mountain House, Alberta, and their relationship to gas production facilities”. Robert J. Wetmiller. Canadian Journal of Earth Sciences. Vol. 23 (1986), P. 172-181.
- ^{xxxi} <https://www.aer.ca/documents/bulletins/AER-Bulletin-2015-03.pdf>
- ^{xxxii} <http://www.aer.ca/documents/orders/subsurface-orders/SO2.pdf>
- ^{xxxiii} <http://csegrecorder.com/articles/view/unintentional-seismicity-induced-by-hydraulic-fracturing>
- ^{xxxiv} <https://www.gov.uk/government/publications/traffic-light-monitoring-system-shale-gas-and-fracking>
- ^{xxxv} <http://www.ukoog.org.uk/knowledge-base/seismicity-kb/what-is-the-industry-doing-to-mitigate-induced-seismicity>
- ^{xxxvi} http://web.mit.edu/10.391/www/proceedings/Geothermal_Prevost2004.pdf
- ^{xxxvii} <ftp://ftp.ingv.it/pub/nicola.pagliuca/Geothermal/1-s2.0-S0013795205003108-main.pdf>
- ^{xxxviii} Stefan Hirschberg, Stefan Wiemer, Peter Burgherr, Energy from the Earth: Deep Geothermal as a Resource for the Future?
- ^{xxxix} <http://www.nlog.nl/en/reserves/Groningen.html>
- ^{xl} <http://www.ogj.com/articles/uogr/print/volume-1/issue-3/understanding-the-science-behind-induced-seismicity.html>
- ^{xli} <http://www.nlog.nl/en/reserves/Groningen.html>
- ^{xlii} <http://www.reuters.com/article/2015/02/18/us-netherlands-gas-groningen-idUSKBN0LM0LG20150218>